**GEAR MEASUREMENT SYSTEM
DEVELOPED UNDER NIST ADVANCED
TECHNOLOGY PROGRAM**
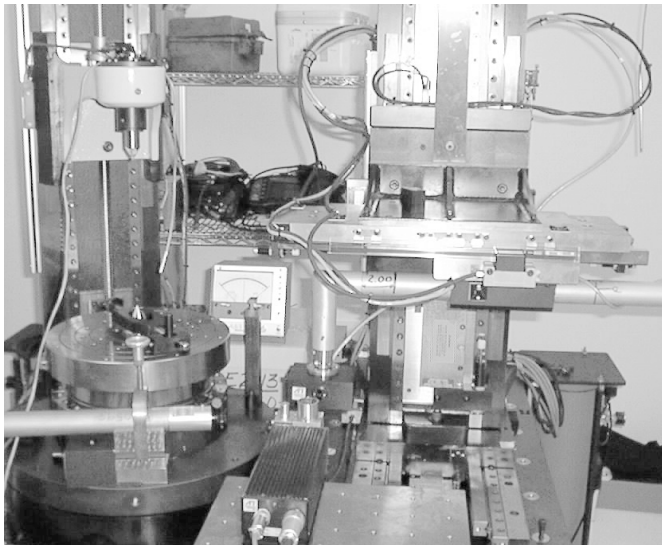
NIST ATP Project Successfully Completed

Accuracies in precision manufacturing are undergoing continuous improvement; in particular, this is true for gear manufacturing accuracies. Dedicated gear measurement systems are manufactured to verify gear manufacturing accuracies. The "Gage Maker's Rule" specifies that measurement accuracy should be at least a factor of ten better than the accuracy of the part being measured; alternatively, the "Minimum Ratio" rule specifies that measurement accuracy should be at least a factor of four better than the accuracy of the part being measured.

In order to maintain these accuracy ratios, M&M Precision Systems Corporation of Dayton, Ohio, with the ARL Penn State Drivetrain Center as principal subcontractor, proposed to the National Institute of Standards and Technology (NIST) Advanced Technology Program (ATP) a project to develop an enhanced-accuracy gear measurement system. M&M's proposal, "Advanced Gear Measurement Technologies to Achieve Submicron Level Accuracies," was one of 29 funded projects out of the 252 proposals received by NIST in the 93-01 ATP competition. The project was successfully completed by M&M and the Penn State Drivetrain Center in June of 1997. The enhanced-accuracy technologies developed by this project will help DoD gear suppliers meet the high-accuracy standards required of their projects. Such enhanced measurement accuracies also will permit improved noise and vibration predictions and reductions for DoD weapon systems to be implemented by ARL MANTECH gear metrology and performance prediction-related projects.

The goal of this project was to develop a gear measurement system capable of a factor of five improvement over the measurement accuracies available in gear metrology equipment in 1993. A two-pronged approach was used to meet this goal: (1) M&M designed and built the QC 9000 gear measurement machine incorporating many new mechanical and control features not available on 1993 vintage gear measurement equipment, and (2) the ARL Penn State Drivetrain Center, together with M&M, developed measurement technologies and computer software to provide error corrections for the consistent components of the measurement errors of the M&M QC 9000 machine. Such consistent measurement errors arise from various geometric and kinematic imperfections in the measurement machine and its scales.

INAUGURAL ISSUE

A U.S. Navy Manufacturing Technology Center of Excellence

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IN THIS QUARTERLY

DIRECTOR'S CORNER

Challenging the 21st Century

I am pleased to introduce you to the inaugural issue of the Manufacturing Science and Advanced Materials Processing Institute (MS&AMPI) newsletter. This newsletter will be published quarterly to keep you informed of progress being made in materials and

manufacturing technology in support of U.S. Navy and Marine Corps weapons systems platforms as well as shipyard and depot requirements. We will also use this newsletter to introduce you to the unique capabilities resident at Penn State's Applied Research Laboratory—one of four U.S. Navy academic research laboratories in the country.

For those of you who are not familiar with MS&AMPI, we are a Department of the Navy Manufacturing Technology (Navy MANTECH) Center of Excellence located on the University Park campus of Penn State. MS&AMPI was established in February 1995 by ARL Penn State. This action was taken at the request of the Office of Naval Research's manufacturing technology director. The Institute provides the Navy with a single point of contact to coordinate the numerous manufacturing technology programs ongoing within ARL. The technical thrust areas currently managed by the Institute include: mechanical drive transmission technologies, materials science technologies, and high-energy processing technologies. Additionally, a repair technology effort for the Navy is also resident. This program is known as Life-Cycle In-Service Repair Networking Coordinator, or LINC. Within the thrust areas noted, attention is focused on materials processing and manufacturing, inspection and testing, quality assurance, and condition-based maintenance.

The technology resources within the Institute provide access to unique capabilities such as spray metal forming, laser processing of materials, cold gas dynamic spraying, electron beam – physical vapor deposition, and ausform finishing of precision gears.

We are tasked to address the materials and manufacturing technology requirements of the Navy and Marine Corps systems commands while quickly and efficiently transitioning our projects into the government acquisition and support infrastructure along with the defense industrial base. Our ultimate goal is to aid the Department of the Navy and the Department of Defense in fielding reliable, state-of-the-art, and cost-effective weapons systems that will maintain our country's competitive edge far into the 21st century.

If you have any questions or ideas on how this newsletter can best serve you, please call me at (814) 865-6345 or e-mail me at: hew2@psu.edu

Henry Watson

| MECHANICAL DRIVE TRANSMISSION TECHNOLOGIES | MATERIALS SCIENCE TECHNOLOGIES | HIGH-ENERGY PROCESSING TECHNOLOGIES | NAVY/MARINE CORPS REPAIR TECHNOLOGIES |
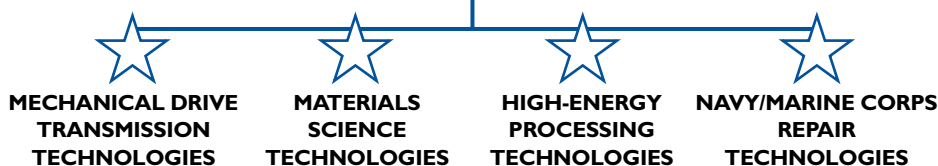
Focus on Mechanical Drive Transmission Technologies

Characterization and Measurement of Heat-Treatment Distortion of Gears[*]

by William D. Mark, Wade H. Reeser, and Robert L. Homan

In order to obtain the desired hardness and strength properties of gear teeth, gears designed for relatively large load-carrying capacities are heat treated after the teeth have been cut. If maximum precision is not required, no finishing operation is carried out after heat treatment. During the heating and cooling cycles of the heat-treatment operation, both volumetric and shape distortions can occur that are caused by thermal gradients within the part, changes in metallurgical structure, material inhomogeneities, etc. The resulting dimensional changes are of sufficient magnitude to seriously affect the performance of gears.

In a recent project, the Penn State Drivetrain Center was asked to measure the heat-treatment distortion of two classes of helical gears finished (before heat treatment) by two different finishing processes. Since heat-treatment distortion is important because it affects the performance of gears, we chose numerical metrics of distortion that are directly relevant to gear performance, but that also can be understood in their own right without regard to gear performance. A discussion of these numerical metrics of heat-treatment distortion follows, together with a brief description of how they are measured and computed, and a discussion of some of the results obtained for one of the classes of helical gears that was finished (before heat treatment) by shaving.

Statistical Characterization of Heat-Treatment Distortion of Gears

In principle, as a pair of meshing gears operates under full loading, every point on the loaded flank of every tooth comes into contact with a tooth of the mating gear. Thus, a complete description of heat-treatment distortion requires that we describe the distortion of the teeth for all locations on the running surfaces of the teeth; i.e., as a function of axial location and roll angle over the full tooth flank. Moreover, we should not assume *a priori* that the distortion of every tooth on a gear is the same. Thus, unless the distortion of every tooth is presented, a *statistical characterization* of the tooth distortions is required.

The noise generated by gears is one of the principal motivating factors for studying their heat-treatment distortion. The *transmission error* of a meshing gear pair describes the noise generating property of the gear pair. Ordinarily, the *tooth-meshing fundamental frequency* and its higher-order harmonics are the most important harmonic components of the transmission error. It has been shown[1,2] that the contribution from the geometric deviations of the teeth on a gear to the tooth-meshing set of harmonics of the transmission error is caused by the *average deviation surface* of the running surfaces of that gear, where this average deviation surface is computed by forming the arithmetic average of the deviations from perfect involute surfaces of all of the teeth on the gear. This average deviation surface is a function of axial location and roll angle. The heat-treatment contribution to this average deviation surface is the surface that would be computed by forming the arithmetic average over all teeth on the gear of the heat-treatment distortions of the relevant flank (right or left flank) of the teeth on that gear. This surface is the *average heat-treatment distortion surface*.

In the noise and transmission error spectra of meshing gear pairs, one often observes a total noise and transmission error contribution from the so-called sidebands around the tooth-meshing harmonics that is comparable to, or sometimes larger than, the contribution from the tooth-meshing harmonics. These so-called sidebands are rotational

PROFILE

William D. Mark, Ph.D., is a senior scientist and project leader for the Metrology and Performance Prediction thrust of the Drivetrain Center. Dr. Mark is a graduate of the Massachusetts Institute of Technology with M.S. and Ph.D. degrees in mechanical engineering. Prior to his arrival at Penn State, Dr. Mark held the position of principal scientist at Bolt, Beranek, and Newman, Inc. Dr. Mark also served as an officer and physicist for the U.S. Air Force Cambridge Research Laboratories.

Dr. Mark is responsible for developing fundamental theory and software for predicting the transmission error of meshing parallel-axis and bevel gear pairs, and for developing methods for carrying out structural dynamics calculations. He also has developed fundamental definitions and interrelationships for the power spectra of nonstationary random processes, the Wigner-Ville distribution, and intensity modulated random processes.

Dr. Mark can be reached by calling (814) 865-3922.

harmonics from each of the two individual meshing gears. Their contribution to the transmission error and noise (for constant loading and rotation speed) is caused by tooth-to-tooth variations in the geometric deviations of the individual teeth from the average deviation surface of each of the two meshing gears.[1,2] The heat-treatment distortion contribution to these geometric deviations of the tooth running surfaces arises from the deviation of the heat-treatment distortion of the running surface of each individual tooth from the above-described average heat-treatment distortion surface. The best single metric of these tooth-to-tooth deviations that can be understood in its own right, and that relates to the transmission error and noise contributions from the "total energy" in the so-called sidebands of the transmission error and noise spectra, is the *variance surface* of heat-treatment distortions computed as an average, over all teeth on a gear, of the squares of the deviations of the heat-treatment distortions of individual tooth running surfaces from the above-described average surface of heat-treatment distortions. This variance surface is a function of axial location and roll angle. The square-root of this variance surface is the *standard-deviation surface* of heat-treatment distortions, which is representative of the *typical* tooth-to-tooth variability of the heat-treatment distortions of the individual tooth running surfaces, and therefore is easier to interpret than the variance surface.

The above discussion has focused on describing properties of the heat-treatment distortion of a single gear. However, these same properties also are applicable as descriptions of the heat-treatment distortion of an entire collection or class of nominally like gears. In addition, however, we need to be concerned with the gear-to-gear variability, within this class, of the various metrics of heat-treatment distortion.

We have described above the relevance of two particular metrics of heat-treatment distortion, namely, the average heat-treatment distortion surface and the variance surface of heat-treatment distortions, both of which can be related to properties of gear transmission error and noise spectra. If we wish to obtain an understanding of the gear-to-gear variability of the contribution of heat-treatment distortion to the tooth-meshing harmonics of the transmission error and noise, then we need to compute the gear-to-gear variability of the average heat-treatment distortion surface obtained from each individual gear within the class of nominally like gears. The *standard deviation of these average heat-treatment distortion surfaces* is a readily understandable metric of this gear-to-gear variability, which is representative of the typical gear-to-gear variability of the average heat-treatment distortion surfaces. This latter standard deviation surface also is a function of axial location and roll angle. It relates, directly, to the gear-to-gear variability of the contribution of heat-treatment distortion to the tooth-meshing harmonics of gear transmission error and noise spectra.

Furthermore, if we wish to obtain an understanding of the gear-to-gear variability of the contribution of heat-treatment distortion to the "total energy" in the rotational or so-called sideband harmonics of the transmission error and noise, then we need to compute the gear-to-gear variability of the variance surfaces of heat-treatment distortion computed from the individual gears in the class of nominally like gears. That is, we need to obtain the variance surface computed as the variance of the individual variance surfaces that were computed from the individual gears in the class. A transformation has been used to reduce this quantity to a numerical metric that is representative of the typical *gear-to-gear variability of the tooth-to-tooth variability of the heat-treatment distortion surfaces within the individual gears* in the class of nominally like gears.

If the average heat-treatment distortion surface, computed from all teeth of all gears in the class, is known with confidence, it is possible, in principle, to compensate for that distortion in the cutting and finishing process of the teeth before heat treatment. The desired tooth surface compensation is, simply, the average tooth distortion surface applied with opposite sign (plus becomes minus and minus becomes plus). Thus, it is of interest to know the *statistical confidence* of the measurement and computation of the average heat-treatment distortion surface. This *statistical confidence surface* is the fifth and last metric of heat-treatment distor-

Table 1. Summary of Computed Heat-Treatment Distortion Metrics and Relevance to Transmission Error and Noise Spectra.

Metrics Relevant to Class-Average Harmonics of Transmission Error and Noise Spectra

Computed Heat-Treatment Distortion Metrics	*Relevance to Transmission Error and Noise Spectra*
Class-average distortion surface (Figure 2)	Class-average tooth-meshing harmonic strengths
Standard-deviation distortion surface of tooth-to-tooth variability of class (Figure 3)	Class-average rotational (sideband) harmonic strengths
Confidence limit surface of class-average distortion surface (Figure 4)	Statistical confidence of class-average distortion for tooth modifications to reduce tooth-meshing harmonic strengths

Metrics Relevant to Gear-to-Gear Variability of Transmission Error and Noise Spectra

Computed Heat-Treatment Distortion Metrics	*Relevance to Transmission Error and Noise Spectra*
Standard deviation of average distortion surface of gears (Figure 5)	Gear-to-gear variability of strengths of tooth-meshing harmonics
Gear-to-gear variability of tooth-to-tooth variability within individual gears (Figure 6)	Gear-to-gear variability of strengths of rotational (sideband) harmonics

tion to be described herein. The above-described five metrics of the heat-treatment distortion of gear teeth, together with their relationships to gear transmission error and noise spectra, are summarized in Table 1.

If gear noise and vibration are the major concerns, it is entirely possible and practical to carry the analysis further by computing the actual contribution to the tooth-meshing harmonics of the transmission error caused by the average heat-treatment distortion surface, and the contribution to the rotational or so-called sideband harmonics of the transmission error caused by the tooth-to-tooth variability in heat-treatment distortion. A reasonably complete characterization then would be obtained by computing the mean value and standard deviation of each of these harmonic line components of the transmission error, which would be obtained from an analysis and computation of the heat-treatment distortions of all of the nominally like gears in the class. An illustration of the transmission-error spectrum computed from measurements of manufacturing errors on gear teeth may be found in references 3 and 4.

Measurement and Computation of Distortion Properties

We describe below the basic ideas behind the method we have used to measure and compute the above-described statistical metrics of heat-treatment distortion. Our approach was to obtain the distortions of both full flanks of every tooth (right and left flanks). An M&M QC 3012 gear analyzer, located at the Penn State Drivetrain Center, was used in making the measurements.

The M&M machine is capable of performing scanning profile measurements (at constant axial locations), scanning lead measurements (at constant radii or roll angles), and point tooth-spacing or index measurements. In order to obtain a representation of an entire tooth flank, a number of scanning profile and/or lead measurements made on that flank at different locations clearly

is required. One can then interpolate between these measurements to obtain a representation of all points on the entire tooth flank.

It was anticipated that the least-smooth heat-treatment distortions would occur near the ends of the teeth, with the center portions of the teeth exhibiting smoother behavior. This thought suggests that the most efficient sampling scheme would be one that requires more dense samples near the ends of the teeth, and less dense samples near the center portions of the teeth. It is known that if samples are taken at the locations of the zeros of Legendre polynomials (after normalization to the interval under consideration), then polynomial interpolation through these sample points is well behaved (i.e., smooth) with the additional property that, in the limiting case of taking very many samples, the interpolation converges (under very general conditions[5]) to the surface (i.e., function) being sampled. Moreover, the zeros of Legendre polynomials have the desirable property of being more closely spaced near the ends of the sampling interval than in the middle of the interval. Therefore, it was decided that 11 scanning profile measurements made on every tooth flank at the locations of the zeros of an eleventh-degree Legendre polynomial should be sufficient to represent, by polynomial interpolation in an axial direction between these measurements, the heat-treatment distortion of all points on each of the tooth flanks. If no *a priori* assumptions are made pertaining to the behavior of the function being represented, it is known[6] that choice of the sample points at the zeros of Legendre polynomials is optimum in the least-squares error sense for polynomial interpolation. It is of interest to point out that the spacing between the two zeros of an eleventh-degree Legendre polynomial nearest to each end of the sampling interval is smaller than the spacing of 22 equispaced samples over the same interval. Hence, by using the Legendre zero sampling method, we could anticipate comparable accuracy to that which would be achieved by using

twice the number of *equispaced* profile scanning measurements! Figure 1 shows the result obtained by polynomial interpolation through 11 such profile scanning measurements made at the locations of the zeros of an eleventh-degree Legendre polynomial on the left flank of a helical pinion tooth finished by shaving.

The method of computing the heat-treatment distortion of the teeth is conceptually simple. Measure each flank of every tooth both before and after heat treatment at "exactly" the same locations on the tooth flanks using the 11 scanning profile measurements on each tooth flank. Subtract the computed space-averaged mean tooth surface from each measured tooth flank of both the before and the after heat-treatment measurements. Then subtract the resulting before-heat-treatment measurement from the resulting after-heat-treatment measurement, on a point-by-point basis, to obtain the heat-treatment distortion of that tooth surface, with the tooth-spacing error contribution, as defined by reference 7, having been removed. It was decided to remove this tooth-spacing error contribution because tooth-spacing errors affect the transmission error and noise very differently from all other types of errors; moreover, its inclusion would make the above-described statistical properties much more difficult to interpret.

In carrying out the above-described measurements, it was very important to retain the identity and "exact" location of every measurement point. In particular, the individual gears and the individual teeth on each gear had to be identified so that the same point could be identified and measured both before and after heat treatment.

In addition to the steps described above, several nontrivial procedures were developed and utilized to ensure that the maximum possible consistency and accuracy would be obtained during the actual measurements and computer analyses of the measurements. This care was considered

essential because the heat-treatment distortion obtained at each measurement location contains measurement errors from both the before and the after heat-treatment measurements.

After the heat-treatment distortions at the above-described measurement locations were computed for both flanks of every tooth, the statistical metrics of heat-treatment distortion described in the preceding section were computed. These computations provided the statistical properties at the 11 locations of the profile measurements made on both flanks of every tooth. Polynomial interpolation between the properties at these locations provided the statistical metrics of heat-treatment distortion illustrated below.

Application and Discussion of Results

Shown below are displays of the five statistical metrics listed in Table 1, measured as described above on the right flanks of a collection of 20 nominally-like helical pinions, each pinion having 20 teeth. All 20 pinions were heat treated in the same batch. The five displays are shown in the same order as listed in Table 1. By recalling that measurements are required both before and after heat-treatment, we note that a total of $2 \times 11 \times 20$
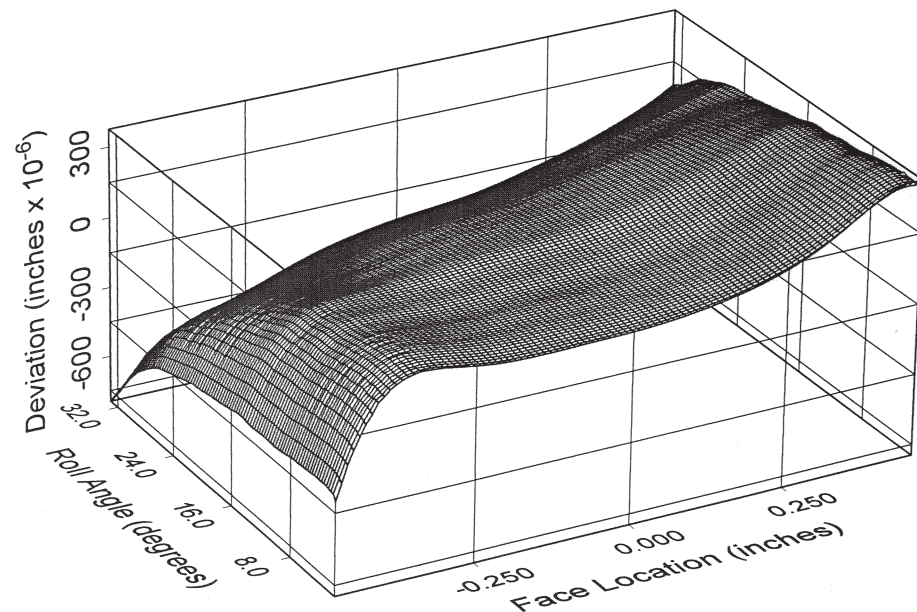
Figure 2. Class-average heat-treatment distortion of right flank of helical pinion teeth. Average formed from distortions of 400 teeth (20 pinions each with 20 teeth).

$\times 20 = 8,800$ individual profile scanning measurements were utilized in generating the results shown in Figures 2 through 6.

Each of these figures displays a plot of the relevant statistical metric as a function of face (axial) location and roll angle. Thus, values are presented for all locations on the right flank of the pinions. Moreover, all statistical metrics are presented in microinches (inches $\times 10^{-6}$) thereby facilitating ease in interpretation. The upper and lower heights of each coordinate box shown in Figures 2 through 6

are determined by the maximum and minimum values of the statistical metric plotted in each figure, thereby allowing quick assessment of the range of values shown.

Figure 2 displays the class-average right-flank distortion, obtained by forming the average of the right-flank distortions from all 400 teeth of the 20 pinions. The minimum and maximum average distortion values are minus 853 and plus 374 microinches, respectively, yielding a total distortion range of 1,227 microinches = 1.227×10^{-3} inches. This quantity is comparable to the elastic deformation of the tooth of a fully loaded steel gear. The behavior of Figure 2 supports our use of more closely spaced profile measurements near the two ends of the teeth (especially the left end). The helix angle on these helical pinions is approximately 27 degrees. The overall distortion shown in Figure 2 effectively tends to "unwind the helix," a well-known effect of the heat-treatment distortion of helical gears.

Figure 3 displays the tooth-to-tooth variability of the heat-treatment distortion, obtained by forming the standard deviation of the tooth distortions utilizing measurements made on the right flank of all 400 teeth of the series. The maximum standard deviation
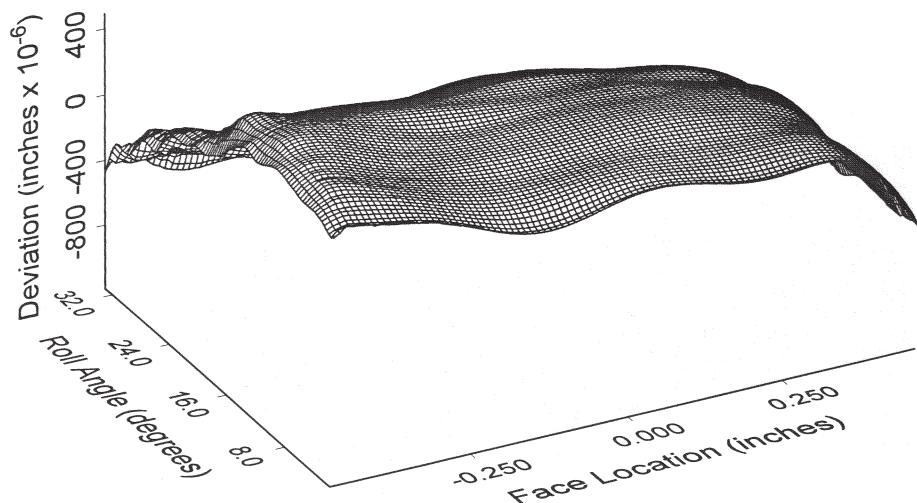
Figure 1. Polynominal interpolation between 11 profiles measured at the locations of the zeros of an eleventh-degree Legendre polynominal (after normalization of the domain of definition). Measurements were made on the left flank of a helical pinion tooth finished by shaving.
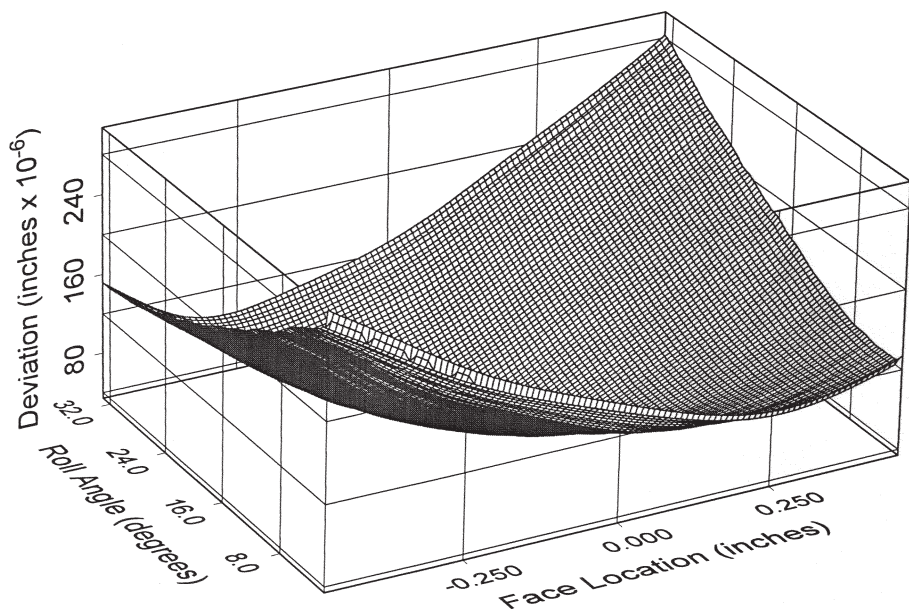
Figure 3. Class-average tooth-to-tooth variability of heat-treatment distortion of right flank of helical pinion teeth. Metric of variability is standard deviation of distortion formed from distortions of same 400 teeth as in Figure 1.
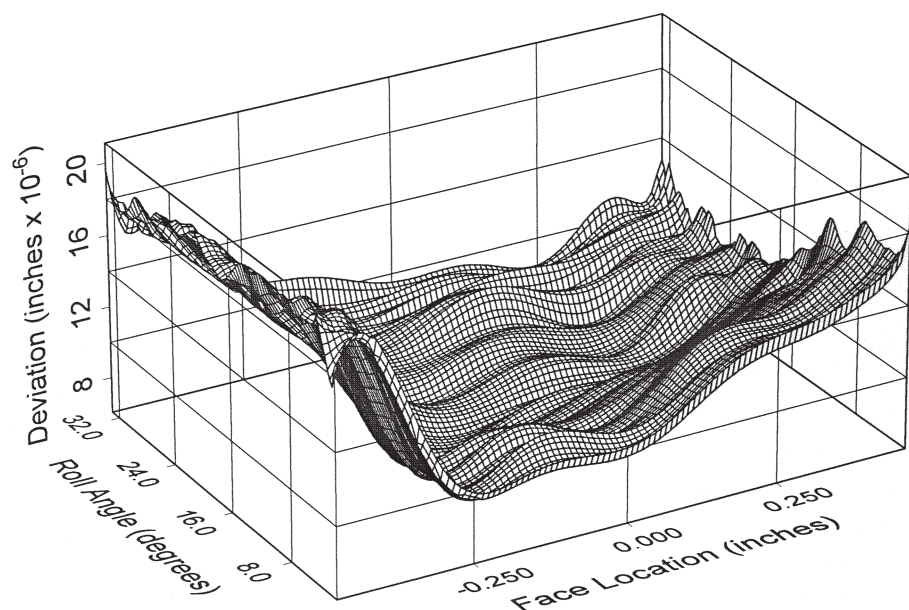

Figure 4. Ninety-five percent confidence limit for error in class-average heat-treatment distortion exhibited in Figure 2. All 20 pinions were heat treated in the same batch.

values shown in Figure 3 are about 300 microinches, which occur at tooth corners that exhibit relatively modest average distortions, as can be seen by comparing Figures 2 and 3. Recalling that one can expect both negative and positive *typical* variations of one standard deviation about the average value, we can expect the minus to plus one standard deviation range of the two 300 microinch corners shown in Figure 3 to

be about 600 microinches, with the excursions of some teeth well beyond these limits. Thus, in these two corners of the tooth flanks, the full tooth-to-tooth variability in heat-treatment distortion is comparable to the average distortion values shown in Figure 2. The tooth-to-tooth variability shown in Figure 3 is sufficient to cause significant pinion transmission error and noise contributions from the rotational harmonics (so-

called sidebands) surrounding the tooth-meshing harmonics.

Figure 4 displays the 95 percent confidence limit for the error in the class-average distortion of the teeth shown in Figure 2. We observe in Figure 4 a maximum value of only slightly over 20 microinches, with typical values of about 10 microinches. This calculation was carried out using the standard deviation of the 20 average distortion surfaces, one such average distortion surface computed from each of the 20 pinions used in the study, together with "student's t" statistics.[8] The results shown in Figure 4 establish that the class-average distortion surface shown in Figure 2 is correct to within about 20 microinches, which is a negligible fraction of the distortion values shown in Figure 2.

Figures 5 and 6 characterize the pinion-to-pinion variability of the statistical metrics shown in Figures 2 and 3, respectively. In particular, Figure 5 displays the typical pinion-to-pinion variability of the 20 average distortion surfaces computed from the individual pinions, one average distortion surface computed from the right-hand flanks of the 20 teeth on each pinion. The maximum standard deviation value shown in Figure 5 is about 45 micro-inches, whereas typical values shown in Figure 5 are of the order of 25 micro-inches. These values are a very small fraction of the class-average distortion values shown in Figure 2. The transmission error and gear noise implication of this result is that there would be relatively little pinion-to-pinion variability in the *tooth-meshing* harmonics of the transmission error and noise caused by pinions within the series of pinions heat-treated and measured in this study. However, it needs to be emphasized that all 20 of these pinions were heat-treated within the same batch. Thus, any potential batch-to-batch source of variability in the heat-treatment process is not included in the surprisingly small variability shown in Figure 5.

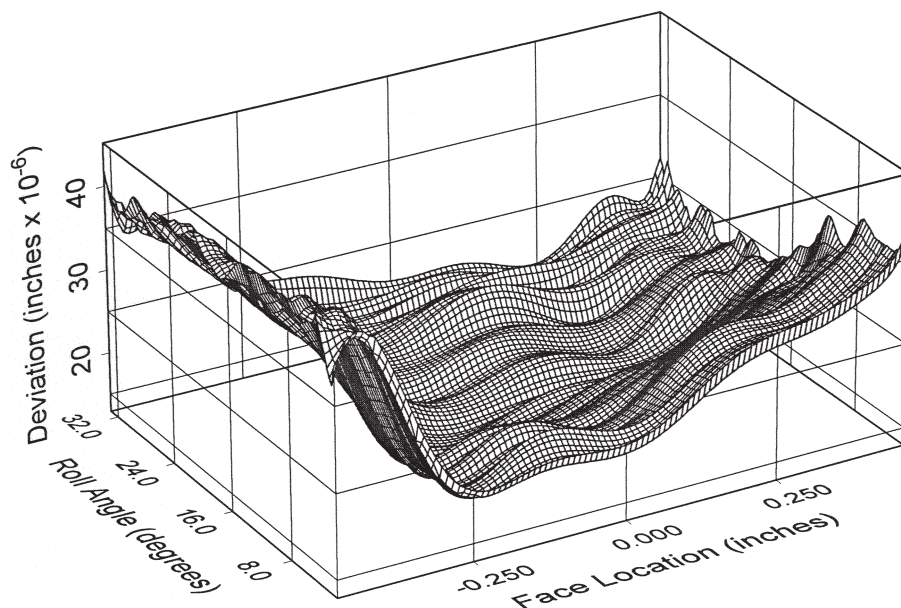The pinion-to-pinion variability of the tooth-to-tooth variability

Figure 5.   Class-average pinion-to-pinion variability of average heat-treatment distortions of the teeth on individual pinions. Metric of variability is standard deviation of the 20 average distortion surfaces, one from each pinion.
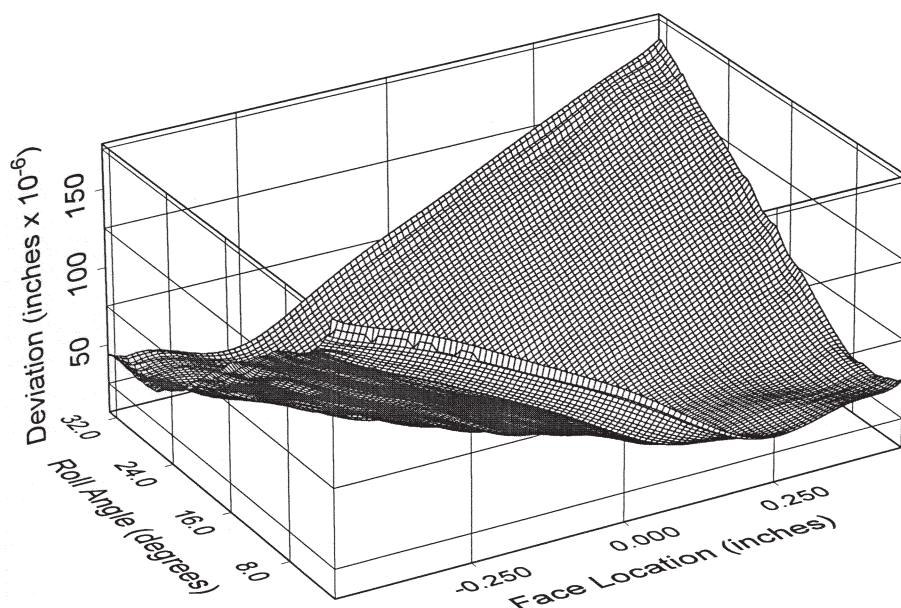

Figure 6.   Class-average pinon-to-pinion variability of variability of heat-treatment distortions of teeth within individual pinions. Metric of variability may be interpreted as pinion-to-pinion standard deviation of the tooth-to-tooth standard deviations of distortion surfaces within the individual pinions.

of the heat-treatment distortion within the individual pinions is shown in Figure 6. Comparison of Figures 6 and 3 is in stark contrast to the comparison of Figures 5 and 2. In Figure 6, we observe a maximum pinion-to-pinion variability of slightly over 175 microinches, which is more than 58 percent of the 300

microinch variability at the same corner of the teeth shown in Figure 3. This result suggests that there would be substantial pinion-to-pinion variability in the "total energy" in the rotational harmonics (so-called sideband harmonics) around the tooth-meshing harmonics of the transmission error, which would result in potentially significant pinion-to-pinion variability in the transmission

error and noise generated by the pinions studied herein.

Our decision to delve into the statistical properties of heat-treatment distortion appears to have been fully justified. Inquiries pertaining to the methodology and results described herein may be addressed to the authors.

Acknowledgment

References

1. W. D. Mark, "Analysis of the Vibratory Excitation of Gear Systems: Basic Theory," *Journal of the Acoustical Society of America*, vol. 63, pp. 1409–1430 (1978).
2. W. D. Mark, "Analysis of the Vibratory Excitation of Gear Systems. II: Tooth Error Representations, Approximations, and Application," *Journal of the Acoustical Society of America*, vol. 66, pp. 1758–1787 (1979).
3. W. D. Mark, "Gear-System Vibrations and Gear Metrology," *ARL Review*, Applied Research Laboratory, Penn State, pp. 200–204, 1994.
4. W. D. Mark, "Gear System Vibrations and Gear Metrology," *National Center for Advanced Gear Manufacturing Technologies Quarterly*, Applied Research Laboratory, Penn State, Winter issue, pp. 4–8, 1994.
5. G. Szego, *Orthogonal Polynomials*, fourth edition, American Mathematical Society, Providence, RI, chapter 14, 1975.
6. F. B. Hildebrand, *Introduction to Numerical Analysis*, Second Edition, McGraw-Hill Book Company, New York, NY, 1974.
7. W. D. Mark, "A Definition of the Spacing Error Between Adjacent Gear Teeth," *National Center for Advanced Gear Manufacturing Technologies Quarterly*, Applied Research Laboratory, Penn State, No. 4, pp. 1–4, 1994.
8. G. W. Snedecor and W. G. Cochran, *Statistical Methods*, eighth edition, Iowa State University Press, Ames, IA, pp. 55–57, 1989.

MS&AMPI Participates in DMC '97

Members of MS&AMPI participated recently in the annual Defense Manufacturing Conference which was held in Palm Springs, California. Leaders from government, industry, and academia assembled to exchange perspectives and information about manufacturing technology and industrial modernization.

This year's theme, "Building Partnerships for the 21st Century," set the forum for discussion about DoD initiatives for increasing manufacturing capability, improving sustainment efficiency, and assuring domestic technology transfer. The agenda provided an executive overview of the scope and level of manufacturing and sustainment programs, followed by technical discussions of the various initiatives and technology thrusts currently being pursued. Keynote speakers included the Honorable Arthur L. Money, assistant secretary of the Air Force for acquisition, Mr. James O'Neill, president, government solutions, Lucent Technologies, and Dr. Renso L. Caporali, senior vice president for engineering and business development, Raytheon Company.

The following MS&AMPI staff members presented papers or participated in poster sessions: Mr. Michael Yukish: "Advanced Simulation and Modeling for Fast, Affordable Manufacturing," Dr. Maurice Amateau: "Joint Strike Fighter Engine Components Produced through Spray Metal Forming," Dr. Paul Kurtz: "Upgrading an Existing Electronic Warfare System Using Modern Technologies and Manufacturing Processes – A Case Study," Dr. Albert Segall: "Development of a Laminated Ceramic Composite Manufacturing Method for Light-Weight Armor," and Dr. Ram Bhagat: "Improved Producibility and Performance of F-107 Compressors Through the Use of Finishing Plasma Coating (Si-O-C) on Cutting Tools."

This year's DMC meeting is scheduled to be held in New Orleans from 30 November through 3 December.

MS&AMPI's Tom Schriempf (left) and Henry Watson (right) pause for photo in front of V-22 aircraft with Yvette Bose, a PMA-275 project engineer.

Staff Visits Naval Air Systems Command

MS&AMPI staff members recently visited the Naval Air Systems Command (NAVAIR) headquarters at Patuxent River, Maryland at the invitation of Colonel Nolan Schmidt USMC, program manager for the V-22 Osprey (PMA-275). The visit provided an opportunity to present an overview of the technological capabilities resident within the institute at ARL Penn State to key project engineers within NAVAIR. A highlight of the visit included a tour of the V-22 manned flight simulator as well as an up-close look at the aircraft itself. Low-rate initial production (LRIP) of the aircraft has begun. Flight test evaluation of the V-22 is currently underway at Pax River. Initial operations capability (IOC) for the Marine Corps' MV-22B is targeted for year 2001.

Sikorsky Test Rig Ready for Action

A two-year refurbishment effort on a six-inch, four-square 150-horsepower gear test rig donated by Sikorsky Aircraft Corporation has been completed. The rig is now ready to conduct critical testing associated with MS&AMPI's Navy MANTECH ausform finishing program. The rig will be an integral part of the project's phase II performance evaluation effort. MS&AMPI greatly appreciates the support Sikorsky Aircraft Corporation continues to provide. For more information on the ausform finishing program, contact Dr. Nagesh Sonti, project leader, at (814) 865-6283 or by e-mail at: nxs7@psu.edu

Six-inch, four-square test rig.

Dr. Tom Schriempf, head of MS&AMPI's High Energy Processing Department discusses laser cladding of an industrial chrome plating replacement components effort for MANTECH with Dr. Davis (2nd from right) and fellow DR&E team members.

Dr. Bard demonstrates portable field application capability of shearography head on AV-8 Harrier jump jet.

Deputy Director, Defense Research & Engineering Visits MS&AMPI

Dr. Lance Davis, deputy director, DR&E, recently visited ARL Penn State as part of a capabilities overview briefing of MANTECH programs. Dr. Davis is also director of laboratory management and technology transfer. Dr. Davis and members of his visiting team were briefed on various on-going projects at ARL Penn State. A tour of facilities followed. The office of the Director of Defense Research and Engineering is tasked with strengthening the strategic planning and assessment processes critical to improving the science and technology (S&T) community's responsiveness to their warfighting and acquisition customers.

MS&AMPI on the World Wide Web

MS&AMPI is now on the Web. Please check us out at: www.arl.psu.edu/core/ms&ampi.html. Changes are regularly being made, so please don't give up trying to reach the site if it is noted as being off-line. We will welcome your comments on how we can fine-tune the site to better serve you.
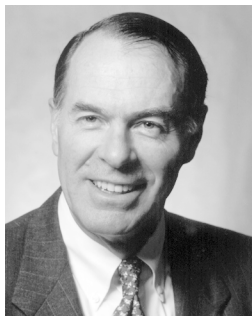
Shearography Project Leader Visits NADEP Cherry Point

Dr. Ben Bard recently visited the Naval Aviation Depot at Marine Corps Air Station Cherry Point (North Carolina). The purpose of the visit was to demonstrate progress on his Navy repair technology (REPTECH) shearography project. Shearography is an optical interferometric technique capable of measuring small out-of-plane displacements. This technique will permit *in situ* inspection of aging aircraft condition, impact damage, and operationally induced damage from extreme loading conditions on both fixed and rotary wing aircraft. For more information on this project, contact Dr. Bard at (814) 865-1870, or by e-mail at: bab132@psu.edu

Singh Earns R&D 100 Award

An ARL researcher who created a novel materials processing technique with a $30 blender and a laser beam has received an R&D 100 award. The award, given by *R&D Magazine*, recognizes the world's most technologically significant process developments. Jogender Singh, a senior research associate in the High Energy Processing Department and associate professor of materials science and engineering, was recently honored by the magazine for his research in the processing of nanoparticles and nanotubes by a novel laser-liquid interaction technique.

The R&D 100 award is an international competition to select and recognize 100 scientists per year for their new discoveries or invention of a new product. This year marks the first time a Penn State researcher has been recognized by the international judging committee set up by *R&D Magazine*. Three years ago, Singh, whose background is in materials engineering, began exploring laser-liquid interactions. He bought a $30 blender from a local department store and modified its blades by flattening them. Then, at ARL's laser laboratory, the blender was filled with a liquid solution and a solid substrate was immersed into it. As the blades rotated at a certain speed, a laser beam penetrated the liquid surface and irradiated the substrate. The thermal energy absorbed by the substrate led to the production of nanoparticles. Afterwards, Singh submitted a grant proposal to the Army, which has been supporting this work ever since. Dr. Singh credits initial U.S. Navy MANTECH project efforts with opening the door to discovering this processing technique. Congratulations Dr. Singh. For more information on Dr. Singh's project, check out "Success Stories" on ARL Penn State's home page Web site—http://www.arl.psu.edu
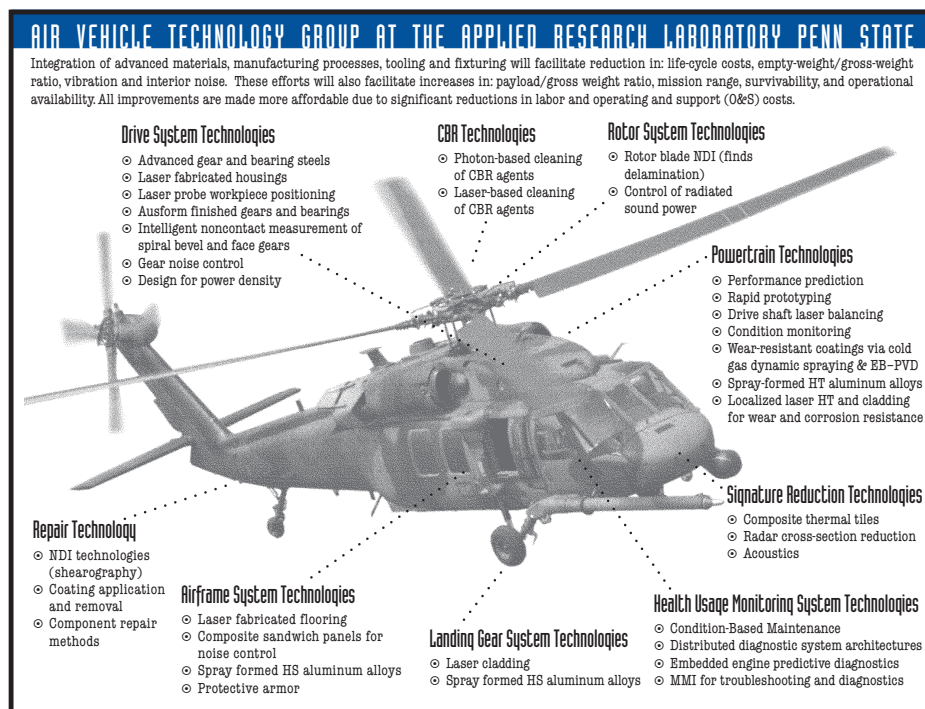
Air Vehicle Technology Group Formed

Within ARL and MS&AMPI, an Air Vehicle Technology Group (AVTG) has been formed to address specific weapons system platform issues relevant to fixed and rotary wing aircraft. This group will integrate areas of expertise within ARL to facilitate reductions in aircraft life cycle costs, empty-weight/gross-weight ratio, and vibration and interior noise. Efforts will also facilitate increases in payload/gross-weight ratio, mission range, survivability, and operational availability. These improvements are made more affordable due to significant reductions in labor costs, and operating and support costs. Mr. Lewis C. Watt will manage the efforts of this group with support from Al Lemanski, Greg Johnson, and Ron Madrid. For a detailed AVTG brochure, contact Greg Johnson at (814) 865-8207 or by e-mail at: gjj1@psu.edu

Lewis Watt

Al Lemanski

AIR VEHICLE TECHNOLOGY GROUP AT THE APPLIED RESEARCH LABORATORY PENN STATE

Integration of advanced materials, manufacturing processes, tooling and fixturing will facilitate reduction in: life-cycle costs, empty-weight/gross-weight ratio, vibration and interior noise. These efforts will also facilitate increases in: payload/gross weight ratio, mission range, survivability, and operational availability. All improvements are made more affordable due to significant reductions in labor and operating and support (O&S) costs.

Drive System Technologies
- Advanced gear and bearing steels
- Laser fabricated housings
- Laser probe workpiece positioning
- Ausform finished gears and bearings
- Intelligent noncontact measurement of spiral bevel and face gears
- Gear noise control
- Design for power density

CBR Technologies
- Photon-based cleaning of CBR agents
- Laser-based cleaning of CBR agents

Rotor System Technologies
- Rotor blade NDI (finds delamination)
- Control of radiated sound power

Powertrain Technologies
- Performance prediction
- Rapid prototyping
- Drive shaft laser balancing
- Condition monitoring
- Wear-resistant coatings via cold gas dynamic spraying & EB–PVD
- Spray-formed HT aluminum alloys
- Localized laser HT and cladding for wear and corrosion resistance

Repair Technology
- NDI technologies (shearography)
- Coating application and removal
- Component repair methods

Airframe System Technologies
- Laser fabricated flooring
- Composite sandwich panels for noise control
- Spray formed HS aluminum alloys
- Protective armor

Landing Gear System Technologies
- Laser cladding
- Spray formed HS aluminum alloys

Signature Reduction Technologies
- Composite thermal tiles
- Radar cross-section reduction
- Acoustics

Health Usage Monitoring System Technologies
- Condition-Based Maintenance
- Distributed diagnostic system architectures
- Embedded engine predictive diagnostics
- MMI for troubleshooting and diagnostics

NIST ATP Project

The M&M QC 9000 machine has three orthogonal linear axes and a rotary axis. A detailed mathematical representation of the kinematic relationships between errors in the three linear axes and the measurement probe errors was developed by Mr. Rajiv Dama, a Penn State mechanical engineering Ph.D. candidate working under the supervision of Dr. William D. Mark of the Drivetrain Center. Using this mathematical model, kinematic errors in the six degrees of freedom of each of the three linear axes, as a function of the probe saddle position along each of these axes, together with the three out-of-squareness errors of these three axes, were mathematically related to the three orthogonal components of the probe position errors. Comprehensive laser and straightedge measurements of the individual axis and out-of-squareness errors then were performed by Penn State and M&M on the QC 9000 machine, from which the probe position errors were computed using the mathematical model. Utilizing this information, corrections to the probe position are made, which are a function of the probe saddle location on each of the three linear axes. A comprehensive set of laser measurements then was made to verify the corrected probe positions.

A unique set of gear-like artifacts was developed by Dr. Mark for use in measuring the rotary-axis errors of the QC 9000 machine. Using a circle-closing principle, these artifacts were used to very accurately calibrate the QC 9000 rotary-axis errors, and these calibrations then were incorporated into the overall four-axis set of error corrections. In addition, a thermal distortion model of the QC 9000 machine was developed by Mr. James T. Moore of Penn State, and first-order corrections to errors induced by temperature gradients within the machine were provided.

The improvements in the mechanical design and controls features of the M&M QC 9000 machine, together with the accuracy enhancements provided by the above-described software error corrections, have resulted in what is probably the most accurate system in the world dedicated to the submicron-accuracy inspection of gears.

CALENDAR OF EVENTS

17 Mar	PSU/ASM International Speaker Series on Aluminum Alloys for Automotive Applications	University Park, PA
19–22 Mar	Convergent Energy Focal Spot Users Seminar	Orlando, FL
30 Mar–1 Apr	Applications of Lasers in Manufacturing Conference	Minneapolis, MN
30 Mar–2 Apr	52nd Manufacturing Society for Machinery Failure Prevention	Virginia Beach, VA
31 Mar–2 Apr	Navy League Sea, Air, Space Maritime Expo '98	Washington DC
21–22 Apr	American Measuring Tool Manufacturer's Association Quality Expo	Chicago, IL
24 Apr	PSU/ASM International Speaker Series on Metals into the 21st Century	University Park, PA
30 Apr–2 May	Manufacturers Alliance, Council on Engineering and Technology	Ojai, CA
4–6 May	National Defense Industrial Association's Vehicle Technology Meeting	Dearborn, MI
20–22 May	AHS Forum 54	Washington DC
10–11 Jun	EB-PVD Workshop at ARL Penn State	University Park, PA
13–17 Jul	TMS 3rd Pacific Rim International Conference on Advanced Materials and Processing	Honolulu, HI
21–23 Jun	International Conference on Agile Manufacturing '98	Minneapolis, MN
23–25 Jun	International Conference on Semi-Solid Processing of Alloys and Composites	Golden, CO
10–14 Aug	Penn State Rotary Wing Technology Short Course	University Park, PA
22–24 Sep	Marine Corps League Force in Readiness Expo	Quantico, VA
12–15 Oct	ASM/TMS Materials Week	Rosemont, IL
16–19 Nov	LIA International Congress on Applications of Lasers and Electro-Optics (ICALEO '98)	Orlando, FL
30 Nov–3 Dec	Defense Manufacturing Conference '98	New Orleans, LA

"A competitive world has two possibilities for you. You can lose. Or, if you want to win, you can change." — *economist Lester Thurow*

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Applied Research Laboratory
P.O. Box 30
State College, PA 16804–0030

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